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Enhancing Forest Sustainability: A Comprehensive Exploration of Thinning Practices and Their Effects on Soil Chemical and Biochemical Properties

Adele Muscolo *, Mariateresa Oliva, Carmelo Mallamaci and Francesco Canino

Department of AGRARIA, "Mediterranea" University, Feo di Vito, 89122 Reggio Calabria, Italy; mariateresa.oliva@unirc.it (M.O.); carmelo.mallamaci@unirc.it (C.M.); francesco.canino@unirc.it (F.C.)

* Correspondence: amuscolo@unirc.it; Tel.: +39-09651694364

Abstract: The adoption of sustainable forest management practices emerged as a contemporary imperative for forest biodiversity preservation, functional integrity, and mitigation of climate change. Within the spectrum of these practices, thinning is recognized as an environmentally sustainable strategy. The primary objective of thinning is the equitable redistribution of aboveground growth, diverting resources from younger trees to promote the accelerated development of more valuable specimens compared to unthinned forests. Thinning, while fostering aboveground changes, induces substantial alterations in soil chemical and biochemical properties. This review addresses the often-debated consequences of thinning on soil characteristics, focusing on the intricate interplay involving different thinning intensities and their impact on soil chemical and biochemical parameters. Specifically, the analysis delves into the modulation of organic carbon levels, microbial biomass, and enzymes crucial to the organic matter cycle. Two key aspects are scrutinized: firstly, the influence of thinning intensity and the temporal dimension post-thinning on soil properties; secondly, the comparative impact of thinning intensity versus the time elapsed from the thinning event on soil properties and associated biological processes. The findings underscore pivotal insights: a) temporal dynamics significantly affect soil organic matter across broadleaved (excluding beech), coniferous, and mixed forests, manifesting as early as 2-7 years post-thinning; b) thinning intensity, up to a threshold of 50%, enhances soil quality by augmenting organic carbon content, bolstering microbial communities, and amplifying associated enzyme activities. This review consolidates valuable information for forest managers, providing guidance to optimize natural processes in tandem with achieving specific management objectives. By illuminating the nuanced interactions between thinning practices and soil dynamics, this knowledge equips stakeholders to make informed decisions in the pursuit of sustainable forest management and ecological resilience.

Keywords: enzyme activities; forest; microbial biomass organic carbon; thinning intensity

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1. Introduction

Thinning, the strategic removal of a specific number of trees from a woodland to redirect tree growth toward fewer, more valuable stems, constitutes a pivotal silvicultural operation essential for effective forest ecosystem management [1]. This practice plays a crucial role in enhancing nutrient availability, productivity, biodiversity [2,3], and processes integral to the soil ecosystem [4]. Forest management practices, in general, exert a profound influence on key factors such as organic carbon storage and sequestration [5,6], nutrient concentrations [7], soil enzyme activities [8], soil biodiversity, and water retention [9,10]. Understanding the impact of forest management practices on soil properties is imperative for preserving the essential functions of forest ecosystems.

Thinning, by reducing tree density, induces changes in microclimate [11–13], resulting in elevated soil temperature and reduced soil moisture [14–17]. This alteration also affects soil properties by increasing compaction [18,19], soil bulk density, and reducing water-holding capacity and nutrient levels [20,21]. Thinning operations, influencing the undergrowth and decomposition in woodland soil, have a substantial impact on the trend of organic matter and the structure of the soil microbial community [22–25], which are crucial determinants of soil quality and health [26–31].

While numerous studies have investigated the effects of thinning on soil organic carbon (SOC) stocks, soil microbial biomass, and enzyme activity, varying and contradictory results have emerged concerning thinning intensity, methods employed, and the time elapsed since thinning [8,31–34]. Moreover, these effects differ across forest types (broadleaf, coniferous, and mixed forest), where differences in litter quality can also influence soil carbon stocks and dynamics differently [35,36].

Through a comprehensive literature review, it became evident that the predominant focus of studies has been on the impacts of thinning intensity rather than the time elapsed since thinning. The effects of thinning intensities and the time elapsed from thinning on soil properties exhibit distinct characteristics. Here, we delineate the key disparities between the influences of thinning intensities and the time elapsed from thinning on soil properties:

1.1. Immediate vs. Long-term Effects

Thinning Intensity:

Thinning intensity predominantly exerts immediate or short-term changes in soil properties. The degree of tree removal and the consequential soil disturbance during thinning operations can promptly affect soil compaction, erosion, and nutrient availability. Higher thinning intensities typically yield more pronounced immediate impacts on soil properties.

Time Elapsed from Thinning:

The time elapsed from thinning refers to the duration that has transpired since the thinning operation was executed. It predominantly influences the long-term or cumulative effects on soil properties. Over time, critical soil processes, such as organic matter decomposition, nutrient cycling, and vegetation regrowth, come into play and shape soil properties. The enduring impacts of thinning become increasingly prominent as the time since thinning extends.

1.2. Magnitude of Change

Thinning Intensity:

The degree of thinning intensity serves as a direct determinant of the magnitude of change in soil properties. Elevated thinning intensities, involving the removal of a larger proportion of trees, typically result in more pronounced and immediate alterations in soil properties. These changes encompass reduced tree competition, shifts in nutrient dynamics, and heightened soil disturbance.

Time Elapsed from Thinning:

The time elapsed from thinning exerts its influence on soil properties in a gradual and cumulative fashion. Changes in soil properties unfold progressively over time, driven by factors such as vegetation regrowth, inputs of organic matter, and the recovery of the soil microbial community. The magnitude of change in soil properties tends to escalate with the duration since thinning.

1.3. Direct vs. Indirect Effects

Thinning Intensity:

Thinning intensity manifests direct effects on soil properties through factors like soil disturbance, alterations in microclimate conditions, and modified nutrient availability arising from reduced tree competition. It directly shapes soil physical and chemical properties, culminating in immediate changes in soil conditions.

Time Elapsed from Thinning:

The time elapsed from thinning predominantly exerts indirect effects on soil properties. This temporal dimension allows for secondary processes to unfold, including vegetation regrowth, shifts in organic matter inputs, and dynamics within the soil microbial community. These indirect effects gradually mold soil properties over an extended period.

1.4. Reversibility

The impact of thinning intensity on soil properties is, to some extent, reversible, contingent upon post-thinning management practices. Implementation of appropriate soil conservation measures can effectively mitigate risks associated with soil compaction and erosion, fostering the gradual recovery of soil properties over time.

Conversely, the effects of the time elapsed since thinning on soil properties tend to be generally irreversible to some degree. Although soil processes and properties may undergo evolution over time, the initial impacts of thinning on soil characteristics cannot be fully reversed. Nevertheless, judicious management practices, coupled with the natural recovery of soil processes, can contribute to the restoration of soil properties to some extent.

In summary, thinning intensities primarily precipitate immediate and direct changes in soil properties, while the time elapsed since thinning exerts a more gradual and cumulative influence over the long term. Thinning intensities exhibit a larger and immediate impact on soil properties, whereas the time elapsed since thinning facilitates secondary processes, influencing soil conditions progressively. Both factors are crucial considerations in forest management, and understanding their distinct effects can inform thinning strategies and long-term soil health management.

This comprehensive review consolidates the latest insights into the influence of various thinning intensities and the time elapsed since thinning, with a specific focus on vegetation types, on soil chemical and biochemical properties. The emphasis is particularly on organic carbon (SOC), soil microbial biomass, and enzyme activity implicated in the organic matter cycle. This consolidated resource aims to provide forest managers with precise information to align thinning practices with specific management objectives, promoting environmental sustainability and positioning thinning as a sustainable forest practice.

Additionally, this review discriminates the effects of thinning on soil chemical and biochemical properties, both crucial aspects of soil analysis that differ in the type of information they provide and the assessment methods employed. Soil chemical properties elucidate the composition and concentration of various chemical constituents, encompassing pH, nutrient levels, cation exchange capacity (CEC), soil organic matter content, and soil texture. On the other hand, soil biochemical properties delve into biological processes, assessing the activities of soil microorganisms, enzymes, and other biological components that impact nutrient cycling, organic matter decomposition, and overall soil health. This distinction allows for a more nuanced understanding of soil fertility, nutrient availability, and overall soil health.

In essence, soil chemical properties focus on the physical and chemical composition of the soil, while soil biochemical properties provide insights into the biological interactions within the soil ecosystem. Together, they offer a comprehensive assessment of soil properties, enriching our understanding of soil health and fertility. The uniqueness of this review lies in its evaluation and discrimination of the effects of thinning intensity and time elapsed since thinning on these distinct yet essential soil properties, providing valuable insights into sustainable forest management practices.

2. Materials and Methods

The current review serves as a robust methodological framework, offering valuable insights to assess theories and evidence within the field. This comprehensive analysis is based on a meticulous examination of pertinent literature and research projects, utilizing diverse sources and search engines, including Scopus, Google Scholar, Elsevier Science Direct, and the Web of Science databases. The data collection process involved strategically chosen keywords, ensuring a focused exploration of relevant topics. These keywords encompassed: thinning, thinning intensity, soil chemical properties, soil biochemical properties, soil organic matter trend, soil microbial biomass, and soil enzyme activities.

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Employing this refined set of keywords facilitated a thorough and targeted retrieval of information. To ensure the inclusion of the latest empirical findings, manuscripts published up until 2023 were meticulously selected for review. This deliberate temporal scope ensures that the synthesis of knowledge within this review is current and reflective of the most recent advancements in the field.

2.1. Thinning intensity effects on soil chemical and biochemical properties

Silvicultural management exerts considerable influence on soil organic carbon (SOC) stocks through its impact on the carbon cycle, microclimate, and soil organic matter (SOM) mineralization, leading to the release of carbon dioxide (CO2). Forest soils harbor a substantial reservoir of carbon, and the implementation of forest management practices raises concerns about potential reductions in soil C stock. This can result from decreased litter input or accelerated decomposition rates due to elevated temperatures and moisture at the soil level. The magnitude of carbon stock in forest soil is intricately linked to factors governing site productivity.

Numerous studies indicate that transitions from primary forests to secondary forests or clear-cut harvesting, involving the removal of wood/tree residues, significantly diminish soil C stock. Conversely, other researchers suggest that thinning intensity may not markedly affect soil C stock [6,35–37]. Thinning intensity within forest stands can influence nutrient availability by reducing tree competition for resources and enhancing organic matter decomposition. It has been demonstrated that thinning intensity regulates biogeochemical cycles in *P. koraiensis* plantation ecosystems by impacting soil nutrients [38]. When accompanied by increased organic matter inputs from litterfall and root turnover, thinning intensity can also enhance soil cation exchange capacity (CEC). Organic matter serves as a source of negatively charged sites that can bind and retain cations, thereby increasing the overall CEC of the soil.

Findings from Settineri *et al*. [20], revealed that high thinning intensity had the most significant impact on increasing the stable fraction of soil organic matter (SOM) and the humification ratio. This indicates a higher degree of humification and a greater CEC [39]. Ma *et al*. highlight that the specific effects of thinning intensity on soil chemical properties can vary based on factors such as initial soil conditions, tree species, climate, and site management practices [15]. Additionally, the interactions among soil chemical properties are complex, necessitating consideration of the overall impacts of thinning intensity within the broader ecosystem context.

Sustainable thinning practices, coupled with appropriate post-thinning site management, emerge as crucial strategies to maintain or enhance soil chemical properties. These practices play a pivotal role in promoting the long-term health and productivity of coniferous stands.

The intensity of thinning significantly influences soil biochemical properties, particularly impacting soil microbial activity—an essential contributor to organic matter decomposition [40]. As thinning intensity escalates, microclimate conditions undergo substantial changes, exerting a pronounced effect on microbial communities and their associated enzymes. Higher thinning intensities can disrupt microbial habitats, leading to a temporary reduction in microbial biomass and activity. Nevertheless, as the ecosystem undergoes recovery and vegetation regrowth, microbial activity rebounds, contributing positively to nutrient cycling processes in the soil.

Extensive research indicates that in both broad-leaved and coniferous stands, soil carbon sequestration predominantly occurs at the forest floor level, with minimal carbon loss observed in the mineral soil (layer 0–30 cm) [41]. Recent studies suggest that to enhance carbon stock in managed forests, it is crucial to increase the spread of the forest floor and to mitigate intensive thinning practices [42]. The impact of thinning intensity on carbon stock in the soil has been a focal point of numerous investigations. Bravo-Oviedo *et al*. demonstrated a decrease in carbon sequestration when an average residual basal area of 65-79% was removed, whereas no reduction was observed with up to 50% basal area removed compared to unthinned conditions or moderate thinning [43,44]. In a meta-analysis, Zhang *et al*. found that light thinning (removing ≤33% of stand basal area or stems volume) increased soil carbon by 17%, while heavy thinning (≥65% removal) decreased soil carbon by 8%. Moderate thinning (33–65% removal) did not significantly alter soil carbon stocks [17].

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Thinning intensity, as studied by Cheng *et al*. [45], exhibited a considerable impact on soil organic carbon (SOC), labile carbon fractions, and soil physical and chemical properties over a short period (2 years). SOC, dissolved organic carbon (DOC), and light fraction organic carbon (LFOC) significantly increased in the heavily thinned plots (36%) compared to unthinned plots. The authors attributed this enhancement to the release of nutrients from the forest floor undergoing rapid decomposition after thinning, contributing to improved soil labile carbon fractions and nutrient availability.

Settineri *et al*. evaluated carbon storage in *Pinus laricio* stands, testing carbon pool trend in forest underwent to diverse thinning intensity (no thinning, moderate (25% basal area removal 1354 N ha^{-1}) and intense (45% basal area removal, 780 N ha^{-1}) and clear cut (Figure 1) in winter and summer seasons, to check if climate (temperature and rainy) influenced at brief time soil carbon pool (Figure 2) [20].

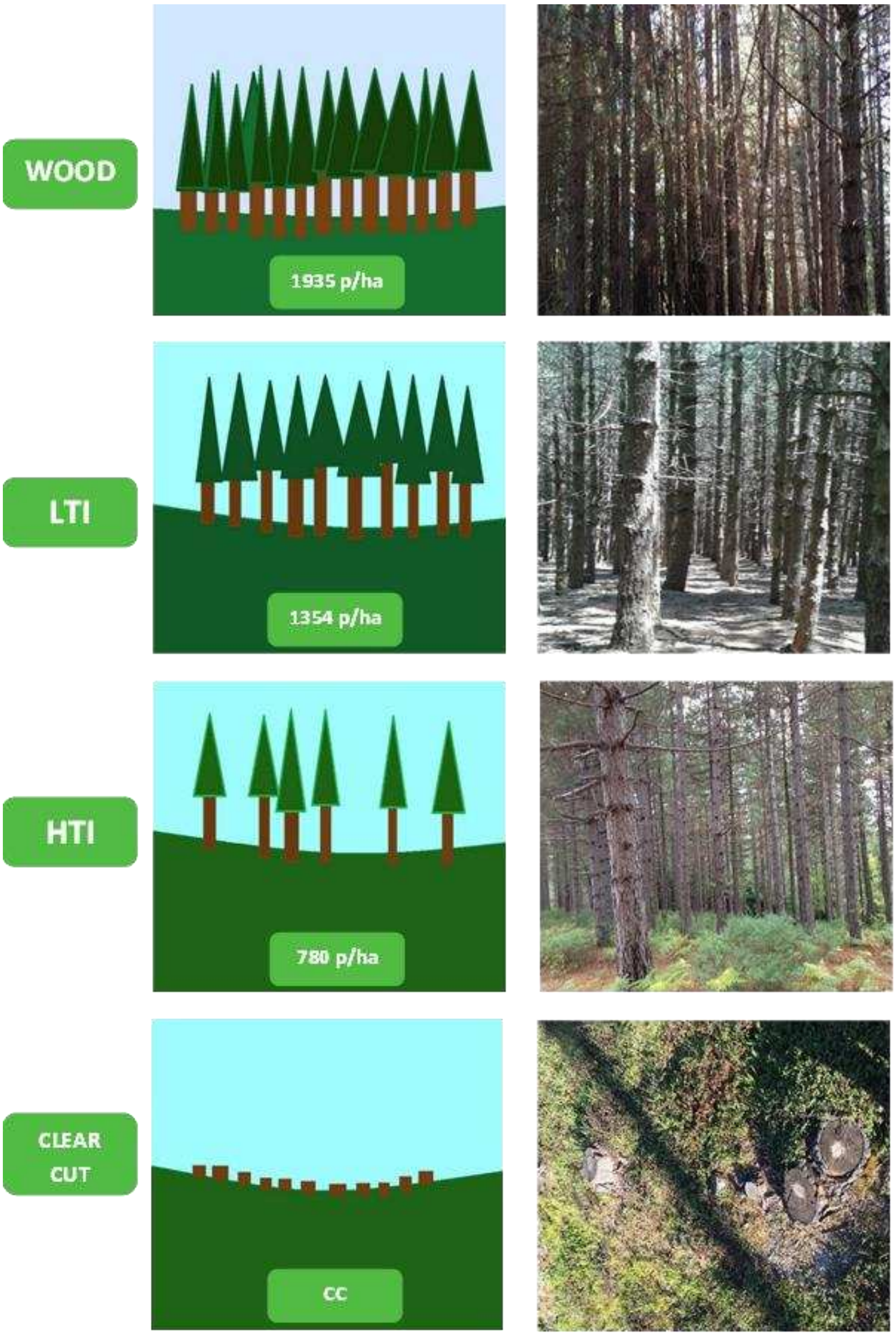

Figure 1. thinning system based on the number of plants removed: low thinning intensity (LTI, 30% plants removed), high thinning intensity (HTI, 60% plants removed), and clear cutting (CC; no plants).

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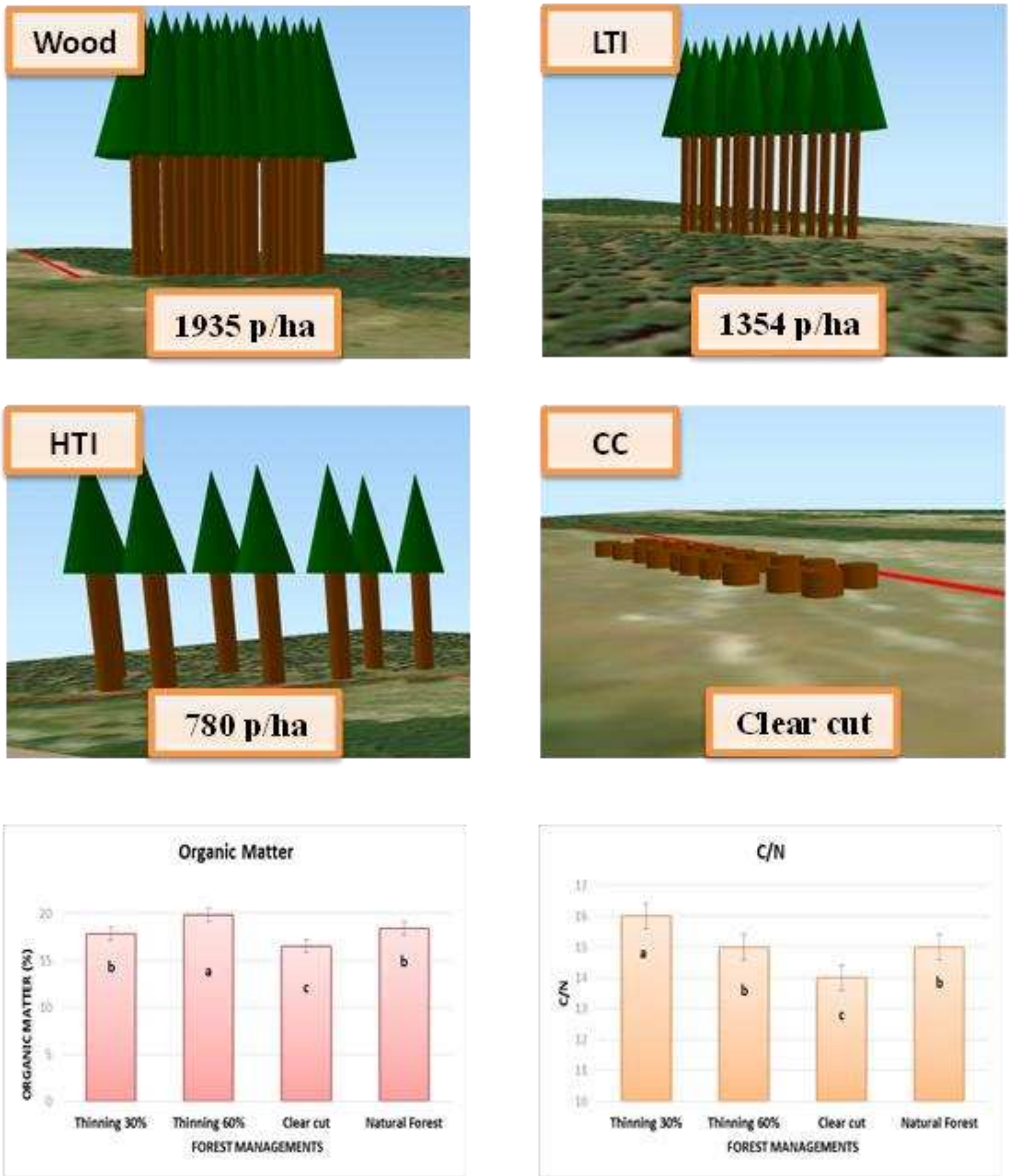

Figure 2.

The authors evidenced that under an intense thinning soil carbon content and carbon/nitrogen (C/N) ratio remarkably increased in respect to the other treatments and possessed as well the highest enzymatic activities, microbial biomass carbon and colonies of fungi and bacteria (Table 1).

Table 1. - Percentage changes in selected chemical and biochemical soil properties due to different thinning intensity related to no-thinning: organic matter (OM); microbial biomass carbon (MBC); fluorescein diacetate hydrolase (FDA); catalase (CAT); dehydrogenase (DHA). Research studies were conducted 4 years after thinning in a Pinus laricio forest (T1*= 25% BA removal; T2* =45% BA) and in a Fagus sylvatica forest (T3§=12% BA; T4§=27% BA) in Apennine, South Italy.

Thinning intensity	OM	MBC	FDA	CAT	DHA
T1*	140	18	28	128	25
T2*	215	25	57	154	89
T3§	-43	-40	3	27	51
T4§	-73	-51	-50	-35	130

These results in short evidenced how the intensity more than season affected soil properties and that independently of the three species the changes occurred in the upper soil layer.

Molina *et al*. studied the middle-time influence of thinning intensity on forest floor and soil properties 13 years after thinning, in a *Pinus Aleppo* plantation [46]. The survey was conducted on plots managed under 3 thinning intensities: high thinning intensity (16% of forest cover, 178 trees ha−1), moderate thinning intensity (46% of forest cover, 478 trees ha−1), and low thinning intensity (64% of forest cover, 689 trees ha−1). Results showed that thinning intensity markedly affected organic carbon fractions in the forest floor, diminishing the quantity of litterfall material coming from the aboveground vegetation. Total organic content, labile and stable organic carbon fractions, and basal respiration were the highest in the forest floor of the not managed plot. On the contrary, remarkable dissimilarity were not seen in the mineral soil for soil carbon fractions under the different thinning treatments. The results evidenced as thinning intensity little impacted on soil carbon accumulation 13 years after thinning. Comparable findings were previously reported [47].

Gong *et al*. carried on a meta-analysis of 270 computations from 77 articles to study how forest thinning influenced SOC stocks in mineral soil (0–30 cm) in planted green wood in China [48]. They found that light (thinning intensity < 35%) and moderate thinning (thinning intensity 35-55%) remarkably raised SOC stocks after five years of recovery, whereas heavy thinning (thinning intensity > 55%) caused a decline in SOC stocks. The variation in SOC stocks were strictly linked to the variation in total nitrogen (TN) stocks. Therefore, forest thinning is considered as an appropriate forest management operation to accumulate carbon in soil.

Yang *et al*. studied, in a pine forest in northern China, four thinning treatments: control (no thinning), light thinning (20% of basal area took away), moderate thinning (40% of basal area took away), and heavy thinning (60% of basal area took away) [21]. Their data evidenced that after 9 years of treatments heavy tinning remarkably decreased SOC by an average of 39.15% in comparison to control. This trend was probable caused by the reduction in litter production, soil nutrients, and fine root biomass. They also identified that heavy thinning (60%) caused the losing of soil C in the pine forest; thus, they advised that less than 60% thinning intensity would be satisfactory to soil C sequestration in managed pine plantations.

Cheng *et al*. put in light that thinning in *Cunninghamia lanceolata* stands in Eastern China did not influenced total SOC, even if thinning positively impacted soil quality. In fact, in the heavy thinning treatment (33%), soil water holding capacity and porosity enhanced in the topsoil layers (0–20 cm), as well as increased total nitrogen, hydrolysable nitrogen, and zinc concentrations [49].

Different results were found by Ma *et al*. that studied how thinning intensity impacted soil structure, organic carbon and labile carbon of larch plantation, in North China [15]. Thinning decreased soil structure of forest in the initial period of thinning, diminished the quantity of macro aggregates weakening their stability. After 7 years of thinning, the storage of soil organic carbon and labile carbon was more in mild (a density of 1835 plants·ha−1, 15% reduction) and intermediate (a density of 1413 plants·ha−1, 30% reduction) thinning plots than in control, and the accumulation of soil organic carbon and labile carbon was less in severe (a density of 1086 plants·ha−1, 50% reduction) thinning plots than in control (a density of 2160 plants·ha−1). The thinning intensity of about 30%

was most favorable to store soil organic carbon and labile carbon in the *Larix principis rupprechtii* plantation.

Settineri *et al*. [20] with a study on thinning operations in a *Pinus laricio* stand, evidenced that the lower density of trees due to the intense thinning practice (60%), caused different light, temperature and humidity intensity at ground and soil levels, enhancing herbaceous vegetation and easy degradable litter, which caused an enhancement of soil microbial biomass and overall, bacteria amount (Figure 3) [20].

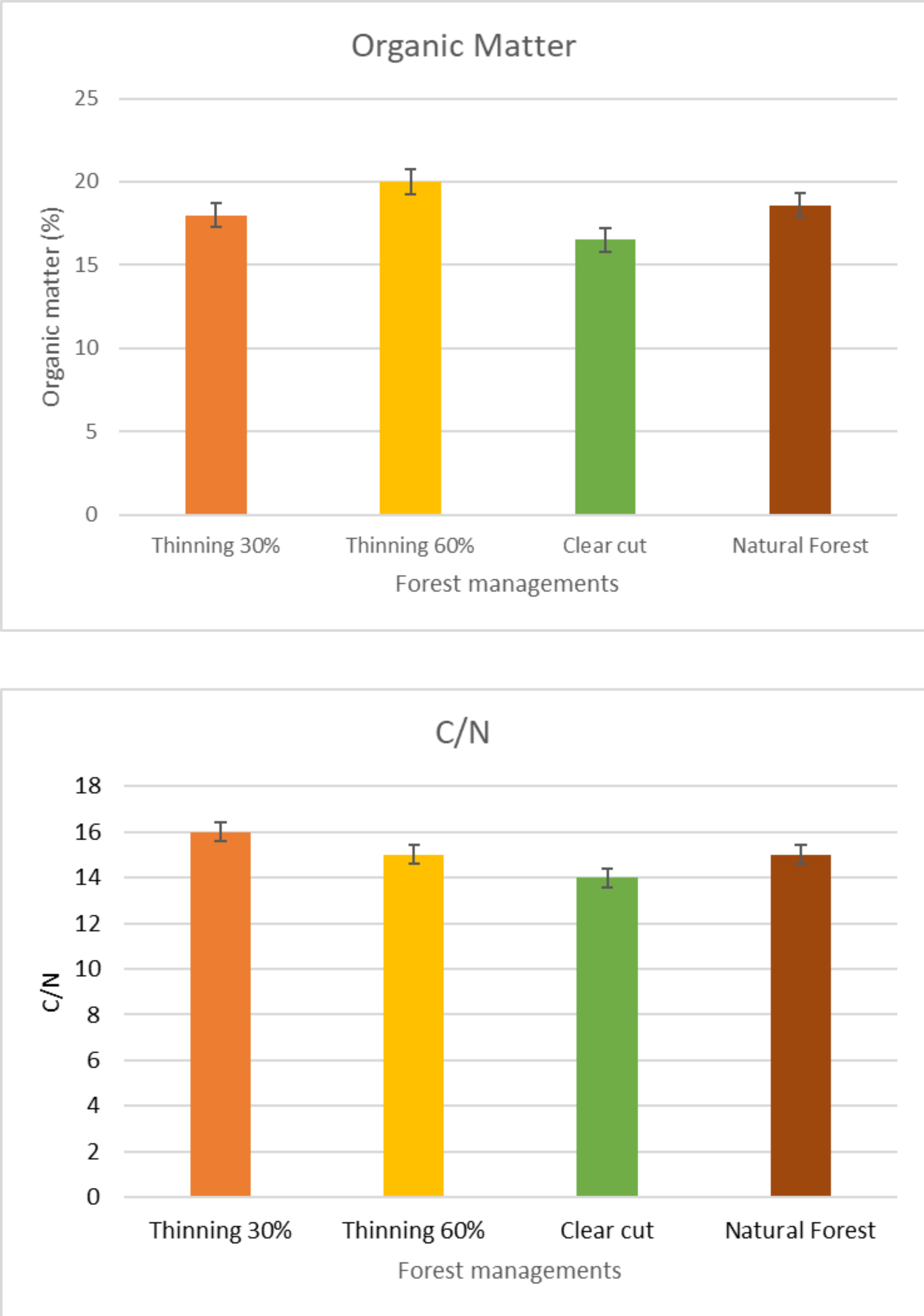

Figure 3. Changes in organic Matter and C/N ratio in a selective" thinning system based on the number of plants removed: low thinning intensity (LTI, 30% plants removed), high thinning intensity (HTI, 60% plants removed), and clear cutting (CC; no plants).

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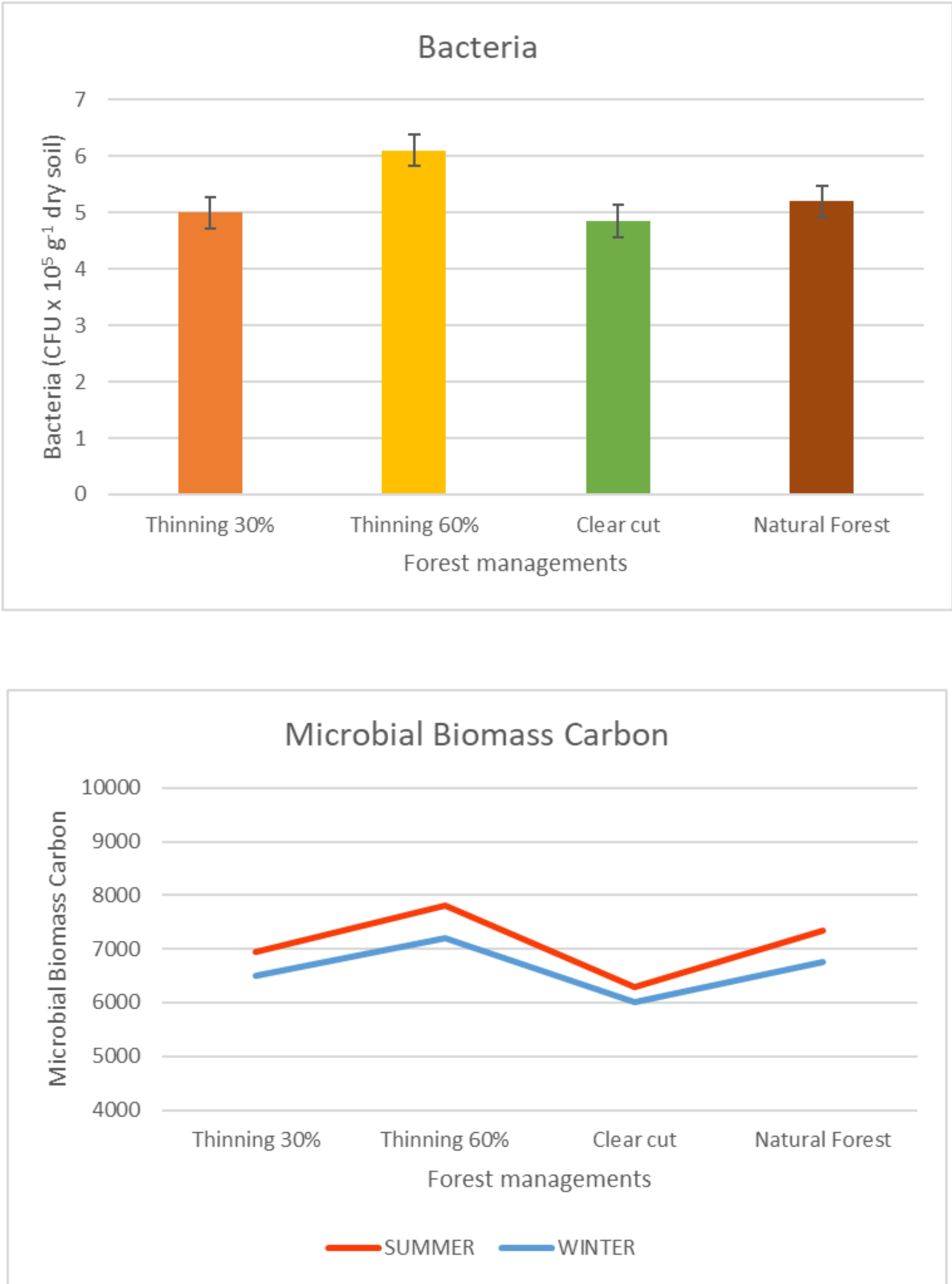

Figure 4. Influence of different thinning intensities based on the number of plants removed: low thinning intensity (LTI, 30% plants removed), high thinning intensity (HTI, 60% plants removed), and clear cutting (CC; no plants) on bacteria amount and soil microbial biomass.

Similar results were also observed by Wu *et al*. in a *Larix principis-rupprechtii* Mayr plantation, in northern China, were medium (35%) and high (50%) thinning positively affected soil organic carbon, microbial biomass carbon, soil microbial abundance, and soil enzyme activities. Actinomycetes and gram-negative bacteria were among the soil microbial community the microorganisms that more affected the function relating to carbon decomposition [29].

Romeo *et al*. [50] used biological indicators (dissolved organic matter (DOC), fluorescein diacetate hydrolase (FDA), catalase, fungi and pedofauna) in a beech forest in Calabria (Italy) to assess as thinning influenced soil properties [50]. The authors evidenced an increase in nutrients, DOC, catalase and FDA enzyme activities and a contemporaneous decrease in SOM in traditional thinning with a moderate intensity (ca. 12% of total volume removed), five years after thinning, putting in evidence that a moderate thinning significantly improved soil quality, emerging as a sustainable forest management practice, even if the organic matter amount decreased. These decrease in SOM under beech may be considered a short-term perturbation induced by thinning. In fact, a study of Tejedor *et al*. (2017) evidenced that thinning in a European beech stand did not remarkably affect SOC stocks at a timescale of ca. one decade after logging, highlighting the goodness of thinning as a sustainable beech forestry treatment from a soil ecological perspective [51].

The results of Romeo *et al*. [50] in agreement with the findings of Bardgett *et al*., Lee and Jose, Allison, De Deyn *et al*. and Billings *et al*. **[50,52–56]**, evidenced that the microflora had a central role in the decomposition of organic matter making nutrients more available for mineral plant nutrition [57]. Furthermore, these data showed that organic matter, total nitrogen, C/N ratio and water content cannot be assumed, alone or in combination, as indicators of soil quality to estimate the consequences of thinning, but it is necessary to cross data of microbiota and ions with organic matter compounds to have more exact information on how the thinning can influence soil biological properties that are closely connected to soil fertility and quality.

Muscolo *et al*. [58], in a *Pinus laricio* stand, found the greatest biodiversity and the highest amounts of arthropods, fungi, and bacteria under intense thinning (45% BA removed, 780 tree ha−1). In summer, the authors observed a greater amount of *Collembola*, *Acarina*, *Diptera*, *Hymenoptera*, and *Pseudoscorpionida*. All these arthropods, have a well-recognized pivotal role in the ecosystem functioning keeping a balance between the decomposition and mineralization of litter and are considered important bio-indicators of soil health [59,60], because they comprehend countless groups that respond rapidly to outer perturbances, varying their distribution and amount in space and time [61]. In winter, the authors observed the apparition of other groups (*Chilopoda*, *Psocoptera*, *Symphyla*, and *Thysanoptera*) that were fully missing either in plots of the other treatments either in high intensity thinning plots in summer.

Results of Caihong, *et al*. [38], in *P. koraiensis* plantation, evidenced as all medium (30%) and high (50%) intensity thinning treatments significantly increased soil nutrient content, including total carbon, total nitrogen, total phosphorus, total potassium, as well as available phosphorus and available potassium. Fungal diversity was higher in both thinned plots but lower in abundance than the control. The results of Caihong *et al* [38] evidenced that thinning intensity modulates biogeochemical cycles by affecting soil nutrients and fungal community structure. Wu *et al*. [29] showed that thinning intensity, improved soil microbial abundance, because caused an in soil organic carbon. The increase in soil microbial abundance caused in turn variation in soil enzyme activities substrate availability [8]. Controversial results such as increase [20,29,31,62], decrease [63,64], or no changes [37,65,66] in enzyme activities resulted from soils under forest management. The variations in soil enzyme activities can be retained responsible for the changes in nutrient dynamics and ecosystem functioning [67].

A meta-analysis [68] pointed out the crucial role of microbial C-degrading enzymes (ligninases and cellulases) in piloting soil C sequestration after thinning. Thinning enhanced SOC stocks, soil labile organic C and recalcitrant organic carbon as well as ligninase activity. These increases have been related to an increase in soil moisture and temperature. Soil cellulase activity diminished when thinning intensity boosted. A rise in SOC stocks after thinning were mostly linked with an increase in ligninase activity. An increment in C-degrading enzyme activity caused by moderate thinning may facilitate microorganisms in harvesting residues and soil organic matter, contributing to the stability of SOC. In short, changes in the activities of soil ligninase and cellulase can explain of how thinning is able to affect SOC pool stability.

2.2. Thinning time effects on soil chemical and biochemical properties

Hwang and Son [69], in a brief-term study evaluated how thinning elapsed time affected forest soils of pitch pine and Japanese larch plantations in central Korea and attributed the increases in SOC and total soil N concentrations after 2 years of thinning (50% of standing density) to the increase in organic matter decomposition and root death, evidencing how the time have a role in influencing thinning effects on soil properties. Numerous subsequent manuscripts have been focused on the role of thinning time on changing soil properties. Rytter et and Rytter [70], studied the effect of 4-8-16 years of thinning on soil characteristics and their results evidenced that pH and bulk density were unaffected during the study period and few significant effects on mineral soil properties after eight years of thinning have been observed. Conversely, numerous studies evidenced that the time elapsed from thinning can have varying effects on soil pH. While there isn't a uniform pattern observed across all studies, the following general trends can be reported: immediately after thinning, there can be a temporary decrease in soil pH. This is often attributed to increased microbial activity and accelerated organic matter decomposition, leading to the release of organic acids that can temporarily lower pH levels. over time, soil pH tends to recover and return towards its initial levels. This recovery can occur through natural processes such as mineral weathering, nutrient cycling, and the re-establishment of a balanced soil microbial community. The recovery period can vary depending on factors such as the intensity of thinning, tree species, soil type, and environmental conditions. Long-term changes in soil pH may occur following thinning. These changes can be influenced by factors such as altered nutrient availability, changes in soil organic matter content, and shifts in microbial community composition. The direction and magnitude of pH changes can be site-specific and may depend on the interplay of various factors [71].

Kim *et al*. demonstrated in South Korea in soil under *Pinus densiflora* that after 7 years thinning enhanced microbial biomass, but did not affect the enzyme activities [66]. Microbial biomass was the highest under 30% basal area thinning and was positively correlated to total soil C and N. Kim *et al*. put in light the relationship between soil properties and microbes showing that the effects of thinning that appeared inconsistent on soil properties, were instead able to change microbial biomass and enzyme functioning in thinned oak and larch forests, in South Korea [8].

Budiaman *et al*., showed as thinning decreased the morphospecies composition of *Entomobryomorpha* and increased the abundance of *Entomobryomorpha* insects [72]. The abundance of the *Entomobryomorpha* order correlated significantly with humidity, litter thickness, and canopy cover that decreased overtime.

Successively, Lull *et al*. evidenced that, in a Mediterranean Holm oak forest, thinning treatment affected a bit soil property and at different extent on the basis of time elapsed since the treatment [73]. After seven years soil carbon pools, basal respiration and enzyme activities were not influenced by thinning treatments.

Xu *et al*. with meta-analysis showed as the time also influenced the thinning effects on soil organic matter trend [68]. Soil C enhanced only in the early stages (≤2 years) after thinning (+30%), but it returned almost comparable to unmanaged stand (control) in the medium (2–5 years) and in the late stages (>5 years) after thinning.

Van Damme et a. showed that surprisingly, no significant difference in the whole ecosystem C stock for after 15 years of management was observed highlighting that the time had less impact on the ecosystem C storage than intensity [74].

Erkan *et al*. in Brutia pine plantations, evidenced that C stocks in the litter, and soil were not significantly influenced by the thinning intensity [39]. The nutrients in the litter and soil, and other soil properties, were not significantly different among thinning parcels. This put in light as changes in C and other nutrients in litter and soil can be ascribed mainly to the stand volume and biomass, which were not changed by thinning in time.

Table 2. Summary of the effects of thinning on organic matter (OM), microbial biomass C (MBC) and enzyme activity (average activity of all enzymes, hydrolytic and oxidative) in different stands studied. ns= no significant changes; + = significant increases; - = significant decreases.

Forest type	Location	Thinning intensity % BA	Years after thinning	OM	MBC	Enzyme activity	References
Larix principis-rupprechtii	Northern China	15	3	ns	ns	+	Wu et al. 2019
		35		+	+	+	
		50		+	+	+	
Pinus sylvestris	Central Spain	15-20 21-35	2	ns	ns	ns	Bravo-Oviedo et al. 2015

Quercus ilex	Valencia, Spain	41	4-7	ns	ns		Lull et al. 2020
Cunninghamia lanceolata	Eastern China	21 36	2	+ +			Cheng et al. 2018
Cunninghamia lanceolata	northern China	15 20 33	15	Ns Ns ns			Cheng et al. 2017
Pinus halepensis	Eastern Spain	36 54 84	13	- - -			Molina et al. 2022
Quercus variabilis, Quercus mongolica, Larix kaempferi	South Korea	5-23 30-44	6	+ +	+ +	ns ns	Kim et al. 2019
Pinus densiflora	South Korea	15 30	7	+ +	+ +	ns ns	Kim et al. 2018
Larix kaempferi	South Korea	20 30	3	+ +		ns ns	Kim et al. 2016
Pinus tabulaeformis	northern China	20 40 60	9	ns ns ns	 + -		Yang et al. 2022
Larix principis-rupprechtii, Pinus tabulaeformis, Betula platyphylla, Quercus liaotungensis	North China	15 30 50	7	+ + +	ns + -		Ma et al. 2022
Pinus rigida, Larix leptolepis	central Korea	50	2	+			Hwang and Son 2006
Pinus nigra	Turkey	30	2	ns	+		Bolat 2014
Pinus massoniana	China	15 70	3	ns -	+ +	- -	Shen et al 2018

3. Discussion and conclusion

In conclusion, this review highlights the importance of considering thinning duration and thinning intensity when assessing their effects on soil properties. While the impact of thinning on soil properties can vary depending on multiple factors, including forest types, plant species, stand ages, management of woody debris, soil characteristics, climate, and temporal factors, some general trends can be observed.

Thinning duration plays a crucial role in shaping soil responses. Studies have shown that positive effects on soil organic matter trends are typically observed in broadleaved (except beech), coniferous, and mixed forests 2-7 years after thinning. This suggests that the short-term benefits of thinning can result in increased soil organic matter content, promoting soil health and ecosystem functioning.

Thinning intensity is another important factor to consider. Research indicates that thinning intensities between 15% and 50% tend to have positive effects on soil quality. These effects include an increase in soil organic carbon levels, enhanced microbial community abundance, and improved soil enzymatic activities. Thus, carefully planned thinning practices within this intensity range can contribute to long-term soil sustainability and support forest management goals.

However, it is worth noting that the specific outcomes of thinning on soil properties can vary based on the aforementioned factors. Therefore, a comprehensive understanding of site-specific conditions and a tailored approach to thinning implementation are essential to achieve desired outcomes.

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Overall, further research on the long-term effects of thinning, considering both duration and intensity, is crucial for monitoring soil ecological responses and informing forest policy management decisions. By integrating these findings into forest management practices, we can enhance our ability to sustainably manage forests, support biodiversity, and promote the overall health and resilience of forest ecosystems.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, Adele Muscolo (A.M.); methodology Francesco Canino (F.C.); software, Mariateresa Oliva (Mt.O.) and validation, A.M. formal analysis, Carmelo Mallamaci (C.M.); investigation, C.M.; resources, A.M.; data curation, Mt.O; writing—original draft preparation, A.M.; writing—review and editing, A.M.; visualization, F.C.; supervision, A.M.; project administration, A.M. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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